

Solid wood joints by in situ welding of structural wood constituents¹⁾

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Abstract

Mechanically-induced wood flow welding, without any adhesive, is here shown to rapidly yield wood joints satisfying the relevant requirements for structural application. The mechanism of mechanically-induced vibrational wood flow welding is shown to be due mostly to the melting and flowing of the amorphous polymer materials interconnecting wood cells, mainly lignin, but also some hemicelluloses. This causes the partial detachment of long wood cells and wood fibres and the formation of an entanglement network in a matrix of melted material which then solidifies. Thus, it forms a wood cell/fibre entanglement network composite having a molten lignin polymer matrix. During the welding period, some of the detached wood fibres no longer held by the interconnecting material are pushed out of the joint as excess fibre. Cross-linking chemical reactions of lignin and of carbohydrate-derived furfural also occur. Their presence has been identified by CP-MAS ¹³C NMR. These reactions are, however, relatively minor contributors during the very short welding period. Their contribution increases after welding has finished, explaining why relatively longer holding times under pressure after the end of welding contribute strongly to obtaining a good bond.

Keywords: wood welding; wood flow; polymer melting; adhesives; lignin; joints.

Introduction

Assembly technologies with mechanical connectors or with adhesives are common in joining solid wood in the furniture, civil engineering and joinery industry. Both kinds of connections show several problems. With

mechanical metal connectors, rust stains may appear on the connectors and corrosion of the connector can and does occur. However, liquid adhesives cause higher costs as regards the upkeep and maintenance of the manufacturing chain. With adhesives, the process is relatively longer unless high investments in adhesive materials and machinery (high-frequency or microwave systems) are made in order to speed up the hardening phase. Thermoplastic welding technologies, which are widespread in the plastic and car industries, have recently also been applied to wood joints, by melting a thermoplastic polymer between the two wood surfaces to be joined. A variety of techniques such as ultrasound, mechanical friction and others (Gfeller et al. 2000; Gerber and Gfeller 2000, 2001; Gfeller and Gerber 2001a, b) have been used to melt the thermoplastic polymer in situ.

This paper deals with the chance finding that the application of the same mechanical techniques at the interface of two solid wood surfaces in the absence of any thermoplastic material, or any other binder, yields joints of considerable strength. The goal of our research was the optimisation of the technology to achieve welded wood joints with high structural strength levels by welding at a very rapid rate. We consider the limits of the present technique and we determine the causes of the mechanically-induced welding by wood flow in absence of any adhesive or welding thermoplastic.

As the term “wood welding” is already used to define the use of a melted thermoplastic resin as the binder of two wood surfaces, this paper refers to the novel process described here as mechanically-induced wood flow welding for lack of a better definition to distinguish it from traditional wood welding.

Experimental

The type of mechanical welding machine used was a Branson welding machine, Geneva, Switzerland, type 2700, 100 Hz, normally used to vibrationally weld metal

Preparation of joints by mechanically-induced wood flow welding

Specimens composed of two pieces of beech wood each of dimensions 150×20×15 mm dimensions were welded together to form a bonded joint of 150×20×30 mm dimensions by exercising a vibrational movement of one wood surface against the other at a frequency of 100 Hz. When the fusion state was reached on the joint interface, the vibration process was stopped. The clamping pressure was then briefly maintained until the solidification of the bond was achieved. The welded samples were conditioned for one week in a climatic

¹⁾Dedicated to Prof. Horst Nimz at his retirement as Editor-in-Chief of Holzforschung (1993–2003)

chamber (20 °C and 65% moisture content (MC)) before testing.

The parameters which were varied in the series of experiments were: welding time (WT=2 to 5 s); contact holding time maintained after the welding vibration stopped (HT=2 to 5 s); welding pressure exercised on the surfaces (WP=0.4 to 2.3 MPa); holding pressure exercised on the surfaces after the welding vibration stopped (HP=1.33 to 2.7 MPa); and the amplitude of the shift imparted to a surface relative to the other during vibrational welding ($A=1$ to 3 mm). The frequency of welding was maintained at 100 Hz as initial experiments at higher frequencies (240 Hz) showed too high a rise in the bond line temperature and lower bond strength due to excessive degradation of some of the materials at the interface. The woods used were beech (*Fagus sylvatica*), a hardwood, and Norway spruce (*Picea abies*), a softwood. The equilibrium MC of the samples was 12%. The effect of water spray on ease of bonding was tested. Several runs were made to determine the bondline temperature. This was obtained by a thermocouple wire inserted at the interface between the two surfaces during the whole process. The specimens which were used for the measurement of the temperature were not used for tensile testing, to eliminate the possible interference by the thermocouple wire.

The tensile strength was measured on samples in which saw cuts perpendicular to the specimens' wood grain, down to the bond line, were made from each of the two surfaces. The distance between the two cuts was 2.5 cm. The specimens were then tested in tension on an Instron model 4467 universal testing machine at a rate of 2 s/mm.

Scanning electron microscopy

Scanning electron microscopy (SEM) was used to analyse (1) the surface of the open joints after mechanical testing, and (2) the waste fibre that accumulated on the surface of the joints during welding after metallizing with gold-palladium. A Hitachi S-520 SE microscope was used at magnifications of 300:1, 1000:1, 2500:1 and 7000:1.

Solid state ^{13}C NMR

The surface of the welded joints obtained were analysed by solid state CP MAS ^{13}C NMR. Both (1) the surface of the open joints after mechanical testing and (2) the waste fibre that accumulated on the surface of the joints during welding were analysed. Spectra were obtained on a Bruker MSL 300 FT-NMR spectrometer. Solid state CP-MAS ^{13}C NMR spectra were obtained for the bonded interface reduced to powder by sanding, the control beech wood powdered by either sanding or grinding and for the ground excess fibre waste coming out at the joints sides. A frequency of 75.47 MHz and a sample spin of 4.0 kHz were used. The impulse duration at 90° was 4.2 μs , contact time was 1 ms, number of transients about 1000, and the decoupling field was 59.5 kHz. Chemical shifts were calculated relative to TMS for NMR control. The spectra were accurate to 1 ppm. The proton spectra were obtained with a sample spin rate of 7 kHz. At this

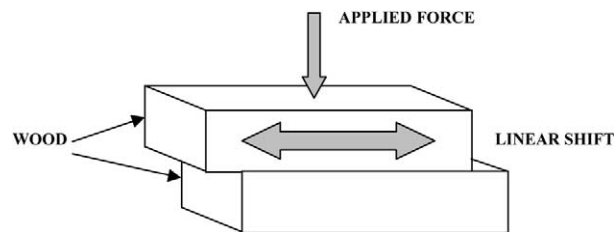


Figure 1 Schematic indication of linear oscillating friction of two solid wood surfaces during wood flow welding.

rate of spin only the water protons can be observed as the wood protons are too large and rigid. These spectra give then a good indication of water mobility in the matrix.

Thermomechanical analysis (TMA) of joints

The wood fusion joints obtained were cut progressively into joints of dimensions suitable for testing by thermomechanical analysis (21 \times 6 \times 1.2 mm). Triplicate samples of these beech wood joints were tested in non-isothermal mode between 40 °C and 220 °C at a heating rate of 10 °C/min with a Mettler 40 TMA apparatus in three point bending on a span of 18 mm exercising a force cycle of 0.1/0.5 N on the specimens with each force cycle of 12 s (6s/6s). The classical mechanics relation between force and deflection

$$E = [L^3 / (4bh^3)] [\Delta F / (\Delta f)] \quad (1)$$

allows the calculation of the Young's modulus E for each case tested. As the deflections Δf obtained were proven to be constant and reproducible (Pizzi 1997; Pizzi et al. 1997), and these are inversely related to the values of the modulus, it is often the values of the deflection (in μm) which have been reported in the tables.

Results and Discussion

The equipment used for frictional welding of wood is the same type of equipment that is used for frictional welding of metal. Figure 1 shows the characteristics of frictional shift and force applied to the two pieces of wood during mechanical welding. The applied welding results were obtained by varying some of the parameters that influence welding of metal with the same type of equipment. Thus, the influence on the final bond of the vibration welding time, the contact holding time after the welding vibration stopped, the welding pressure exercised on the surfaces, the holding pressure after the welding vibration stopped, the amplitude of the shift imparted to a surface relative to the other during vibrational welding was tested. Two different species of wood were compared, beech (a hardwood) and Norway spruce (a softwood). The majority of the experiments were done with beech wood because the bonding results on Norway spruce were less encouraging. This was due to the interference of cell wall collapse on bonding. Cell wall collapse is a well-known problem in this wood species.

Table 1 Parameters used for the optimisation of mechanically-induced wood fusion welding. Variations of vibration amplitude, welding time and welding pressure, and results obtained by test in tensile of bonded joints.

Amplitude (mm)	Welding time (s)	Welding pressure (MPa)	Joint tensile strength (MPa)
Beech wood			
1	3	0.4	–
1	4	0.4	–
1	5	0.4	–
3	3	0.4	–
3	4	0.4	1.43
3	5	0.4	3.48
1	3	1.3	–
1	4	1.3	–
1	5	1.3	–
3	3	1.3	5.43
3	4	1.3	6.96
3	5	1.3	6.74
1	3	2.3	–
1	4	2.3	–
1	5	2.3	–
3	3	2.3	5.86
3	4	2.3	7.61
3	5	2.3	5.37
Spruce wood			
1	5	2.3	0.5
3	3	0.8	1.5
3	4	0.8	2.0
3	5	0.8	1.7

Bonding results

The initial bonding experiments reported in Table 1 compare the influence of welding time, welding pressure and vibration amplitude on bonding strength. From the results in Table 1 the following conclusions can be drawn. Joint tensile strength depends on vibration amplitude, with the joint presenting no bonding strength at all for 1 mm vibrational amplitude and presenting some good bonding results for 3 mm vibrational amplitude. Joint tensile strength also depends on welding pressure: the higher

the welding pressure in the range used, the higher is the bond strength of the joint. The only exception to this is the last case for beech wood in Table 1, where for the pressure used the joint strength starts to decrease. This is due to temperature-induced incipient degradation of the bond. Joint tensile strength further depends on welding time. This dependence, however, appears to be less intense than that of welding pressure. At each pressure while bond strength in general increases with welding time the increase is not too marked, good results being obtained both at 3, 4 and 5 s welding time, at parity of all the other conditions. While it appears from Table 1 that softwoods can be frictionally welded too, the problem of cell wall collapse characteristic of the softwood species chosen renders it impossible to arrive at definite conclusions as regards the potential of softwood welding.

Furthermore, the initial experiments reported in Table 1 indicate that wood flow welding is potentially very promising, with the best average result of 7.61 MPa not being very far from the 10.0 MPa strength value for a structural wood joint required by the relevant European Norm EN 205-D1.

Tables 2 and 3 show the results obtained by the combination of different welding times, holding times after end of vibration welding and holding pressure after end of welding. The influence of water sprays on the wood surfaces was also tested. Some of these parameters appeared to be determinant in obtaining joint strengths comparable and higher to the requirements of the relevant standard. The best results were obtained with the shortest welding time (3 s), but at a longer holding time (5 s). In this case, the results are much better than relying on a longer welding time (4 s) (Table 1), but on much shorter holding time (2 s). Two of the average results reported in Table 3 actually satisfy the requirements of the relevant EN 205-D1 specification, while at least three other sets of conditions yield results very close to requirements of the standard.

Increasing welding times decreased joint bond strength under the range of conditions tested. The higher of the two welding pressures, at 2 MPa, yielded the best results. Higher welding pressures than this, such as 2.3 MPa in Table 1, yielded worse results due to incipient

Table 2 Parameters used for the optimisation of mechanically-induced wood fusion welding.

Series	Welding time (s)	Welding pressure (MPa)	Holding time (s)	Holding pressure (MPa)	Water spray (g/mm ²)	Number of specimens tested
1a.	3	1.3	2	1.3	No	10
1b.	3	1.3	2	2	No	10
1c.	3	1.3	5	1.3	No	10
1d.	3	1.3	5	2	No	10
1e.	3	1.3	5	2	yes	10
2a.	4	1.3	2	1.3	No	10
2b.	4	1.3	2	2	No	10
2c.	4	1.3	5	1.3	No	10
2d.	4	1.3	5	2	No	10
2e.	4	1.3	5	2	yes	10
3a.	5	1.3	2	1.3	No	10
3b.	5	1.3	2	2	No	10
3c.	5	1.3	5	1.3	No	10
3d.	5	1.3	5	2	No	10
3e.	5	1.3	5	2	yes	10

Table 3 Results of tensile strength tests according to European Norm EN 205 of mechanically-induced wood fusion welding specimens cases outlined in Table 1.

Series	Tensile strength (MPa)	S.D.	S.D. (%)	S.E.
1a.	3.64±1.3	1.7	47.9	0.6
1b.	2.26±1.8	2.2	98.8	0.8
1c.	9.40±1.2	1.3	14.0	0.5
1d.	10.45±0.9	1.1	10.2	0.4
1e.	10.37±1.0	1.3	12.8	0.4
2a.	1.18±0.4	0.4	37.4	0.2
2b.	0.86±0.2	0.3	32.2	0.1
2c.	8.78±0.8	1.1	12.0	0.4
2d.	6.41±1.2	1.7	25.8	0.6
2e.	8.47±0.8	1.1	12.6	0.4
3a.	0.82±0.3	0.3	41.1	0.1
3b.	0.51±0.2	0.3	51.1	0.1
3c.	7.54±0.8	0.9	12.4	0.3
3d.	4.55±1.3	1.7	36.9	0.6
3e.	4.44±1.2	1.5	34.6	0.5

S.D. = Standard Deviation.

S.D.% = Standard Deviation %.

E.S. = Standard Error.

bond degradation. The presence or or absence of water sprays did not appear to affect the result. Initially, water sprays were tried to see if increased moisture content would further promote lignin flow. This did not appear to be the case; the 12% equilibrium moisture content seemed to be more than sufficient (Figure 2). The temperature at the glue line reaches 170 °C during welding; no increased moisture content will be maintained in such a hot interface, and as such water sprays have no effects. It must be noted that while at the bondline the maximum temperature is 170 °C, in the wood just 1 mm away from the bondline the temperature is equal to ambient temperature (20 °C–25 °C). This maintenance of a remarkably low temperature in the body of the joint explains observations that the high temperature reached (exclusively at the interface) does not distort the joint.

Results not reported here have shown that the strong joints obtained are not capable of satisfying any relevant specification for exterior joints, as they present very poor resistance to water (Zanetti and Properzi unpublished results). In standard tests for exterior grade joints, immersion of the joint in boiling water is used. The very high water content and the high temperature allow again considerable flow of the melted matrix. This is because the high water content and high temperature used under these testing conditions place the bondline at a temperature much higher than the glass transition temperature of the matrix lignin. These joints can then be only considered for interior applications such as for furniture and for interior grade joinery.

Bonding mechanisms

CP-MAS ^{13}C NMR A series of analyses of the joints by scanning electron microscopy (SEM), by solid state ^{13}C NMR, by FT-IR, and by thermomechanical analysis (TMA)

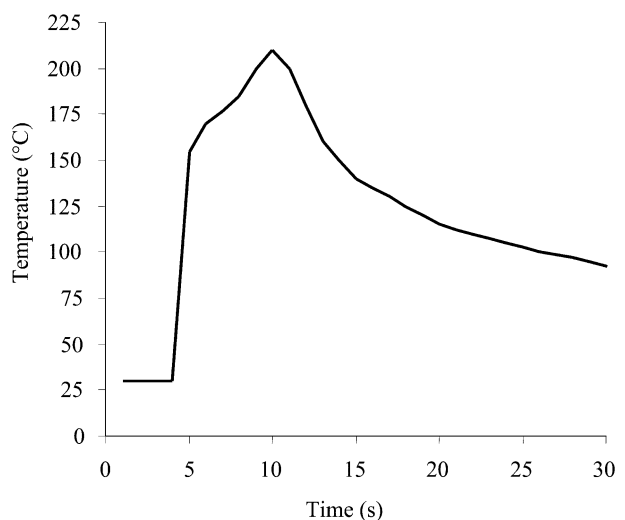
was carried out to understand the mechanisms involved in wood flow welding.

Figure 3 reports the detail of the 120–175 ppm region of the CP-MAS ^{13}C NMR spectrum for the wood of the bondline (less than 0.5 mm on each side of the bondline) of a wood flow-welded beech joint welded for 3 s and held for 5 s. This region of the spectrum is characteristic of lignin. The sample was obtained by sanding. This spectrum is compared with the CP-MAS ^{13}C NMR spectra details of untreated beech wood controls obtained by sanding and by grinding (Figure 3), and of the considerable amount of excess fibres which are expelled from the joint sides during welding and which have veritably undergone the same process (Figure 3), also obtained by grinding.

The general CP-MAS ^{13}C NMR spectra (not reported here) indicated that not many differences in the wood carbohydrates appear to exist in the samples other than a relatively higher proportion of crystalline cellulose in the excess fibres (the C4 at 88.47 ppm of crystalline carbohydrates is more clearly visible). The main differences between the spectra are however in the smaller signals in the region 120–175 ppm, characteristic of some of the signals of lignin (but not exclusively). To facilitate observation of the differences in this region of the spectra, their details are compared in Figure 3.

Figure 3 shows a main peak at 153.4/153.9/154.1 ppm characteristic of the carbon of an aromatic ring to which is bound a –O–, be it an –OH or an –OCH₃. The main lignin aromatic carbon to which a –OCH₃ methoxyl group is bound can be seen at 161.2 ppm. The absence of this latter peak in the excess fibre and in the sanded beech control indicates that lignin in the glue-line does not appear to be too heavily demethoxylated, while the fibres expelled during welding contain heavily demethoxylated lignin. The number of peaks in this region represent aromatic ArC–O– presenting different substitution patterns of the aromatic ring.

Of particular interest are the pronounced signals at 149.1 ppm and at 148.2 ppm in the samples from the welded bondline and from the welding excess fibres which are almost completely absent in the sanded beech

**Figure 2** Typical bondline temperature increase during wood flow welding time and holding time (case 3 e, Table 3).

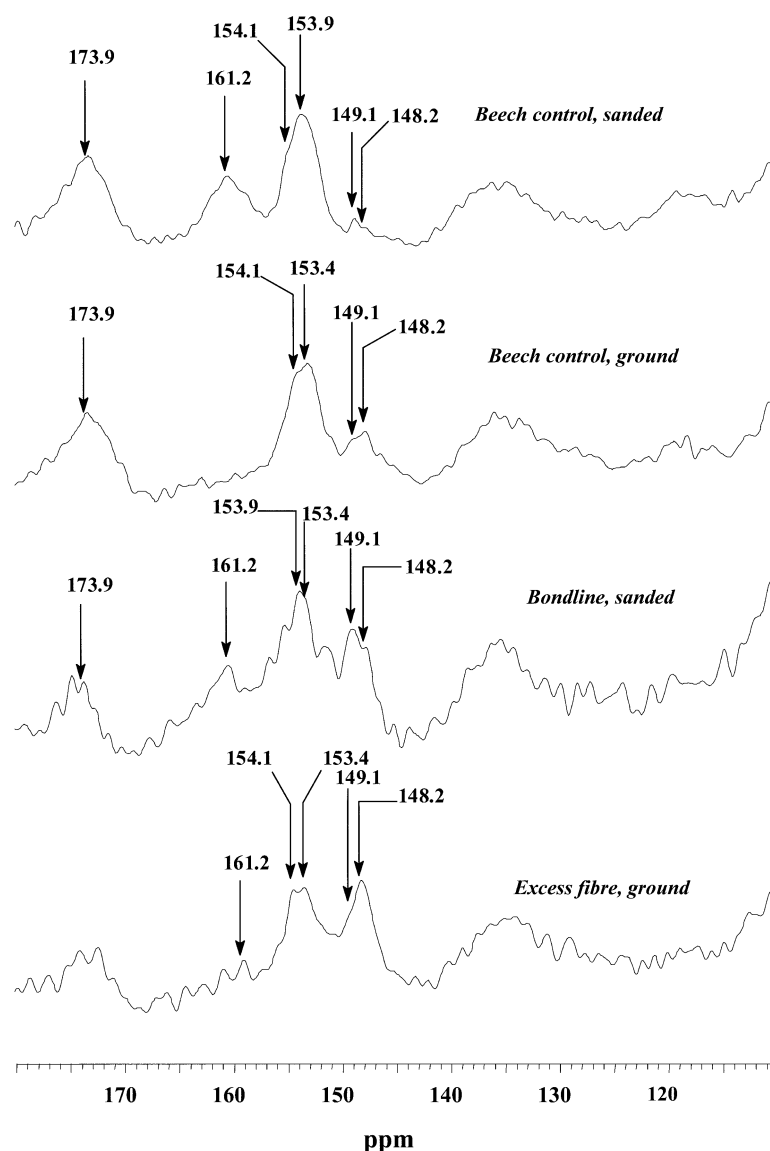


Figure 3 Comparison of detail of 120–175 ppm regions of CP-MAS ^{13}C NMR spectra of finely sanded and finely ground control beech wood samples, of finely sanded beech wood material in the bondline and of finely ground excess fibres issued during welding from the bondline.

control, and are very small in the ground beech control (Figure 3). Of these, the 149.1 ppm corresponds to an aromatic carbon bound to a non-aromatic carbon, namely (Ar)C–C, but which deviates from the “normal bonds” which occur in lignin. Alternatively, it could be of the same (Ar)C–C type present in lignin but in greater abundance compared to native lignin. This indicates that a reaction on the aromatic ring of lignin has occurred, which is also demonstrated by the number of peaks visible in this crowded region: one passes from 7–8 visible in the sanded beech control to the 10 present in the sanded bondline sample and in the excess fibres (Figure 3). This finding could be due to partial demethoxylation of the lignin moiety.

Most interesting is the signal at 148.2 ppm characteristic of the carbons of a furan ring (Pretsch et al. 1989) (Figure 3). Furfural, methyl furfural and other furanic materials are well known to be obtained from wood carbohydrates (Fengel and Wegener 1989), probably from the hemicelluloses, by thermal treatment. The high tem-

perature reached during welding (Figure 2) indicates that the formation of furfural in the glue line is quite likely and the presence of its 148.2 ppm signal confirms its presence both in the bondline and in the excess fibres. The slightly higher proportion of it on the excess fibre (Figure 3) is logical if one considers that this is the material which has undergone the most marked mechanical treatment. It is not present at all in the sanded beech control, and it is present to a much smaller extent in the ground beech control (Figure 3). However, the lack of a signal of an aldehyde function indicates that this material is self-polymerised and probably reacted with the aromatic ring of lignin.

The clear –COO– acetic acid signals at 173.5 and 173.9 ppm of beech hemicelluloses, which can be observed in the two controls, decrease markedly in bondline and excess fibre samples. They also resolve in a series of smaller peaks some of them with a shift characteristic of levulinic acid, obtained with furfural from the same type of reaction (Fengel and Wegener 1989). This

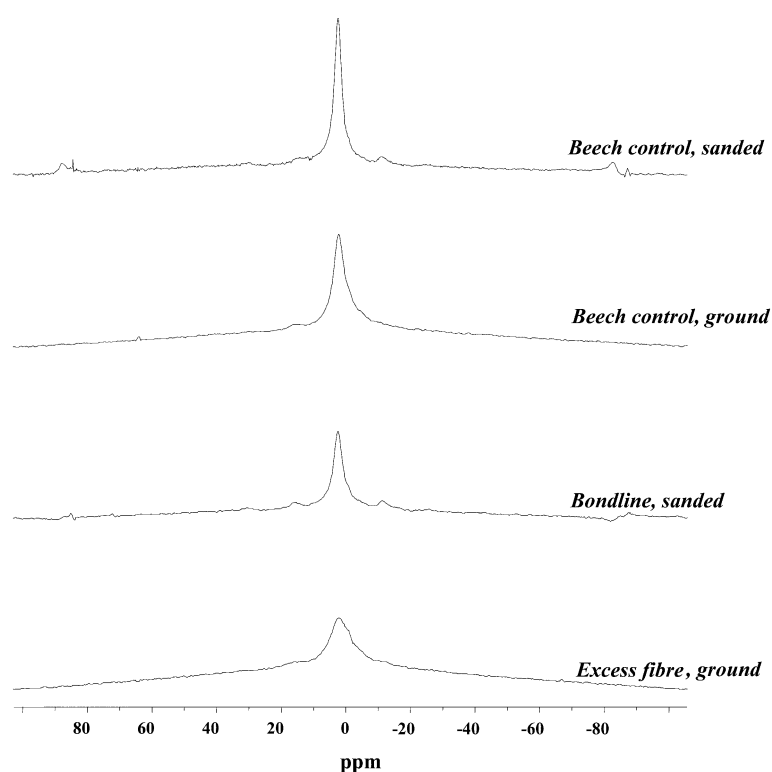


Figure 4 Comparison of NMR proton mobility spectra for the materials in Figure 3.

indicates that welding has heavily deacetylated the hemicelluloses and that this free acid has helped to catalyse the formation of furanic compounds at higher temperature during wood welding.

In short, the results of the NMR analysis indicate that (1) a certain amount of lignin demethoxylation has occurred during welding; (2) the proportion of amorphous carbohydrates appears to slightly increase during welding; (3) a reaction of autocondensation of lignin on its aromatic ring appears to have occurred; (4) furfural appears to have been produced during welding and to have self-polymerized or reacted with lignin aromatic nuclei, or both; and (5) some deacetylation of hemicelluloses occurred during welding, the free acetic acid possibly contributing to the occurrence of the preceding reactions.

Although the results indicate that some self-condensation and/or cross-linking reactions involving lignin and furfural occur, their limited extent does not appear to justify the joint bond strengths in excess of 10 MPa obtained in wood flow welding (Table 3). These reactions are surely a contributory factor, but they are unlikely to be the main cause of the bonding results obtained in mechanically-induced wood flow welding.

NMR water protons mobility

The higher the moisture content in wood, the lower is the glass transition temperature of lignin and hemicelluloses, hence the lower is the temperature at which it is possible for them to melt and flow. Thus, a first indication that the main cause of wood flow welding might be a physico-chemical effect due to some wood constituents melting rather than just a cross-linking chemical reaction comes from the water proton mobility NMR spectra of the four

main samples shown in Figure 4. These show weak interactions of water with wood in three of the samples with the intensity of the interaction increasing as the signal becomes less sharp, hence passing from the sanded beech control, to ground beech control and to the bondline.

The interaction of water with the excess fibres was considerably stronger as shown by the much broader proton signal in Figure 4. The higher the water interaction, the lower is the T_g of hemicelluloses and lignin (Kelley et al. 1987) and the easier it is to melt these two materials or for these two materials to flow (Kelley et al. 1987; Pichelin et al. 1998). This means that melting of hemicelluloses and lignin appears to have taken place during welding, particularly in the excess fibres, and to a lesser extent in the bondline. An occurrence that has clearly not taken place in the two controls.

Scanning Electron Microscopy (SEM)

If melting of some of the major structural and polymeric wood constituents occurs, this should be observed by scanning electron microscopy. Figure 5 shows one of the characteristic bands on the surface of fusion welded wood. One can see fibres, long wood cells or tracheids immersed in a mass of amorphous, molten polymer. As the cells do not appear to be greatly damaged, it means that melting has occurred mainly in the intercellular connecting tissue or middle lamella. Wood middle lamella is particularly rich in lignin. Figure 6a and b, which show a detail of the excess fibres expelled from the bondline during welding, confirm this. They show that the fibres are entire, undamaged, long wood cells and the material that is seen on their surfaces, interconnecting them in patches, is definitely part of damaged, melted cell-intercon-



Figure 5 Scanning electron microscopy images of lignin fusion band on the bondline with cellulose fibers and wood cells (tracheids) immersed in it obtained during welding at magnification 300 \times showing general appearance of the band.

necting material, hence mainly lignin from the wood middle lamella.

The SEM investigation thus visually confirms what was partly inferred by the CP-MAS ^{13}C NMR spectra. The mechanism of mechanically-induced vibrational wood flow welding is due mostly to the melting and flowing of amorphous cell-interconnecting polymer material in the structure of wood, mainly lignin, but also some hemicelluloses. As a consequence, the elongated wood cells partially detach from each other and from the underlying wood structure. They form an entanglement network encased in a matrix of molten material which then solidifies. In short, a wood cells entanglement network composite having a molten lignin matrix is formed. During the welding period some of the detached wood cells which are no longer held by the interconnecting material are expelled from the joint as excess fibre.

Thermomechanical Analysis

The description in the preceding paragraphs is not, however, complete. The CP-MAS ^{13}C NMR spectra indicated that some cross-linking chemical reactions of lignin and of carbohydrate-derived furfural also occurred. These contribute to the mechanical resistance of the joint, although to a minor extent. The results of constant heating rate thermomechanical analysis (TMA) of welded bondline joints indicates an increase of the modulus of elasticity (MOE) of the joint at increasing temperatures (Figure 7). The increase occurs in two distinct steps, which suggests a distinct series of chemical reactions going to completion only after welding has occurred. These chemical cross-linking reactions contribute further to the strength of the joint, but only come to bear after welding has finished. This might well be one reason why

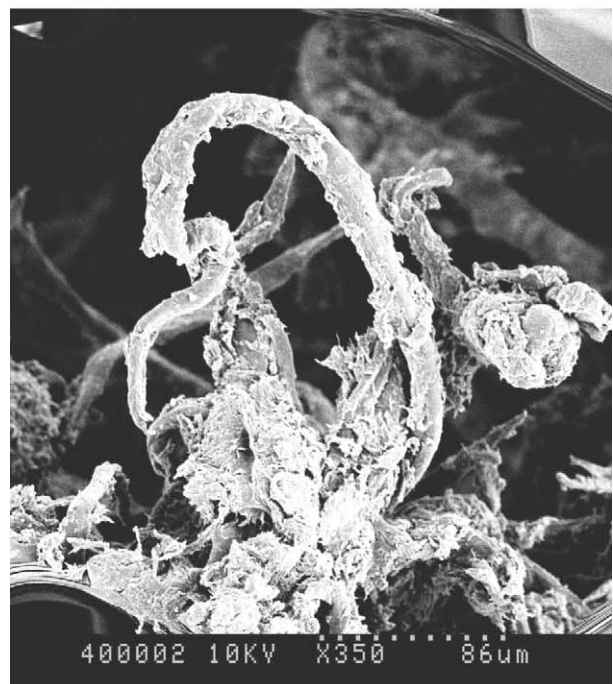
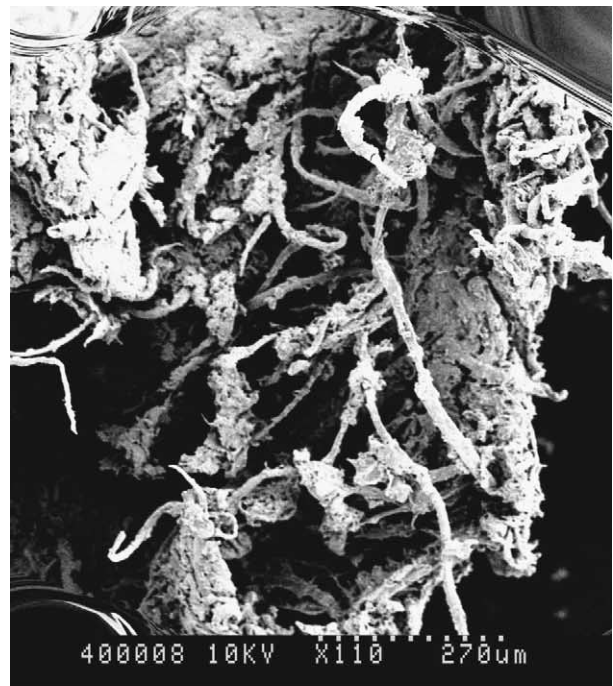


Figure 6 Scanning electron microscopy images of entangled detached wood cells (tracheid) from the excess fibres issued from the bondline during welding at (a) 110 \times and at (b) 350 \times . Note the fused amorphous residual material clinging to the tracheids surfaces from the intercellular bonding material holding wood cells together.

the longest holding time under pressure after the end of welding has such a strong contribution to a good bond (see Table 3). After all, the increase in MOE with heating in Figure 7 is quite marked. These reactions might well be the completion of the initial reactions which have been observed by NMR, hence an increase in strength due to some increase in cross-linking due to reactions of lignin and/or furfural.

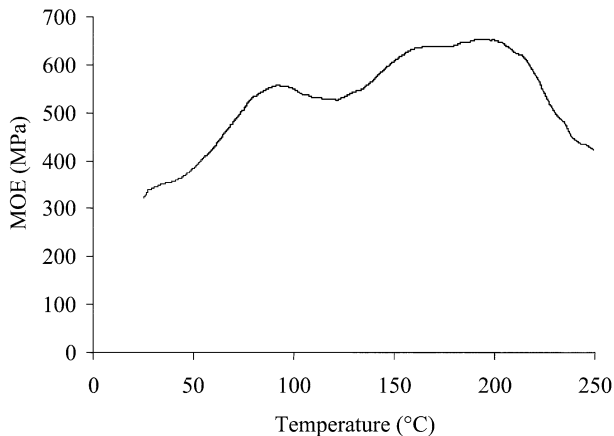


Figure 7 An example of the curve of the increase in modulus of elasticity (MOE) as a function of time and temperature obtained by thermomechanical analysis, at a constant heating rate of 10 °C/min, of a beech wood joint obtained by mechanically-induced wood flow welding. Note the further increase in MOE with the temperature indicative of residual cross-linking reaction after welding and limited holding.

Conclusions

Mechanically-induced wood flow welding, without any adhesive at the interface, yields joints satisfying the relevant requirements of structural wood joints. Although the joints are acceptable only for interior use as they are not weather or water resistant, this technique opens the doors to effective and inexpensive gluing of solid wood without adhesive for furniture and for interior joinery. The mechanism of mechanically-induced vibrational wood flow welding is due mostly to the melting and flowing of amorphous cells-interconnecting polymer material in the structure of wood, mainly lignin, but also some hemicelluloses. This causes partial detachment of wood cells from the underlying wood structure. A network of long wood cells is formed, encased in a matrix of molten material which then solidifies. In short, a wood cell entanglement network composite is embedded in a molten lignin matrix. During the welding period some of the detached cells are pushed out of the joint as excess fibre. Cross-linking chemical reactions of lignin and of carbohydrates-derived furfural also occur, but are minor con-

tributors during the very short welding period. Their contribution increases after welding has finished, explaining why relatively longer holding times under pressure after the end of welding contribute strongly to obtaining a good bond.

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